Metallurgy Department. Progress Report for the Period 1 January to 31 December 1982

Risø National Laboratory, Roskilde

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Metallurgy Department Progress Report for the Period 1 January to 31 December 1982

Risø National Laboratory, DK-4000 Roskilde, Denmark
July 1983

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METALLURGY DEPARTMENT PROGRESS REPORT FOR THE PERIOD 1 JANUARY TO 31 DECEMBER 1982

Abstract. The activities of the Metallurgy Department at Risø during 1982 are described. The work is presented in three chapters: General Materials Research, Technology and Materials Development, Fuel Elements. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1982 is included.

INIS-descriptors: FUEL ELEMENTS, METALLURGY, NONDESTRUCTIVE TESTING, RESEARCH PROGRAMS, RISOE NATIONAL LABORATORY.

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1. INTRODUCTION

The time schedule for the establishment of nuclear power in Denmark is still uncertain. Risø is therefore at stand-by in this field but a number of the nuclear programmes are continued in order to ensure up-to-date knowledge. In the Metallurgy Department the nuclear work comprises projects within design and testing of fuel elements, fracture mechanics studies in pressure vessel steels and non-destructive testing. The projects concentrate more and more on advanced problems, which in many cases are studied in collaboration with other parties in Europe and abroad. An example of such a problem is fission gas release in Zircaloy-UO_2 rods after high burn-up. The first international programme in this area "The Risø Fission Gas Project" was executed in 1980-81. The second programme "The Risø Transient Fission Gas Release Project" was started in 1982. These programmes are sponsored by a number of firms and organizations in Europe and abroad. Other examples are fracture toughness studies of irradiated pressure vessel steels of various origins (as part of a collaborative IAEA programme) and acoustic emission investigations of welds (under the auspices of the European Coal and Steel Community).

With respect to alternative energy technology a major effort was devoted to fibre reinforced plastics. These materials are used for wing-blades for small and medium-size wind turbines built, respectively, by a number of Danish industries and a group of electricity generating companies. The projects within this area are related to design, manufacture, testing and failure analysis. In the testing area a large programme is fatigue properties of fibre reinforced plastics (sponsored by the Ministry of Energy). Other energy projects include metal-hydrogen systems (e.g. for transportation and storage of energy) and solid ion conductors for use in rechargeable batteries. These projects are partly carried out under the auspices of EEC, The Nordic Fund for Industrial Development and the Ministry of Energy.

In order to promote generally the fibre materials technology in Denmark a semi-scale fabrication facility was expanded with the financial support of the National Agency of Technology. This facility, which includes a filament winding machine, autoclaves and testing equipment, was used extensively for industrial contract work outside the energy field.

Work was done under contract for industries and utilities in Denmark and abroad. Due to their proprietary nature, most of these activities are excluded from the present report. Among the major nuclear activities were fuel element development, where collaboration with the Elsinore Shipyard was continued, isotope analysis and post-irradiation examinations of fullscale power reactor rods (Zr-UO_2 and Zr-UO_2-PuO_2).

Other work on contract was done on high-temperature components for the chemical industry. In this context the department joined the European COST-501 project, "High Temperature Materials for Conventional Systems of Energy Generation and Conversion using Fossil Fuel". The departments project is entitled "Metal Dusting", metal dusting is a high temperature corrosion phenomenon. This project is carried out in collaboration with a Danish firm and partly sponsored by the Ministry of Energy. In the area of non-destructive testing the work was concentrated on quantitative ultrasonic examinations, especially the characterization of sound fields. The many discussions to obtain patents on "The Risø Tube Inspection System" were continued and one new patent (in Japan) was obtained. Further projects were centered on the development of materials and processes, including ceramics for measurement of oxygen potentials in combustion gases, sintering of nuclear ceramics, and brazing technology. In the field of neutron radiography standardization work was continued together with the neutron radiography working group sponsored by Euratom.

To support the technological programmes of the department a large effort was as usual devoted to fundamental problems, e.g. radiation damage in metals, strength/structure relations in single-phase and two-phase materials, and structures in ceramics.

This work was published in the open litterature and for further information the reader is referred to the list of publications which includes abstracts. A large part of the fundamental work is carried out in collaboration with universities and research laboratories in Denmark and abroad.

The department participated in international collaboration on specific research projects and also in a number of international projects and study groups under the auspices of the NEA, EEC and various Nordic and US organizations.

The department organized the 3rd Risø International Symposium on Metallurgy and Materials Science, 6-10 September 1982. The title of this symposium was "Fatigue and Creep of Composite Materials". The symposium was attended by approximately 100 participants presenting 36 papers. Planning was started for the 4th Risø International Symposium to be held at Risø 5-9 September 1983. The title of this symposium is: "Deformation of Multi-phase and Particle Containing Materials".

Educational activities were continued; students and post-graduates from Denmark and abroad studied in the department.

GENERAL MATERIALS RESEARCH

Additive strengthening

(In collaboration with the Department of Metallurgy and Materials Science, University of Cambridge and The Danish Academy of Engineering).

The study of additive strengthening in copper containing a dispersion of alumina particles was continued with quantitative structural analyses in order to obtain more accurate estimates of the strength contributions from the metal matrix and the dispersed particles.

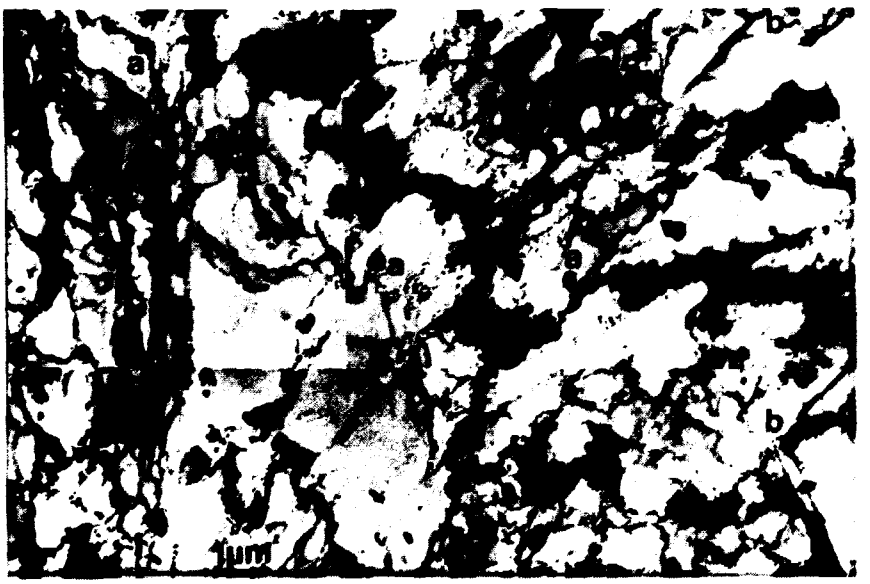

Fig. 1. A montage of transmission electron micrographs covering most of one grain of a copper specimen containing 0.41 volume percent alumina after a tensile strain of 0.2. Some segments of the encompassing grain boundary are arrowed. The alumina particles in the matrix (examples are labelled a) give rise to higher local dislocation densities than do those at the grain boundaries (examples are labelled b).

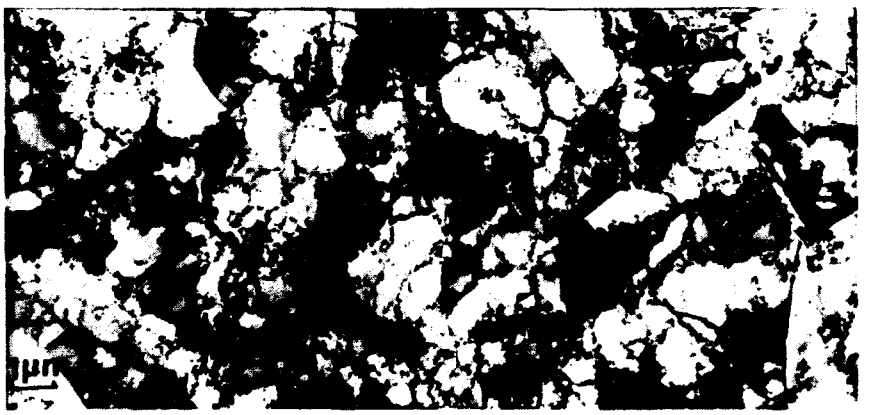

Fig. 2. A montage of transmission electron micrographs covering most of one grain of a specimen of pure copper which had been subjected to a tensile strain of 0.2. Some segments of the surrounding grain boundary are arrowed. A clear cell structure is developed across the grain with some parts of the grain boundary region showing smaller cells.

Deformation mechanisms were studied in aluminium containing dispersions of large and small particles. The bulk behavior was studied by transmission electron microscopy and surface displacements during deformation were followed by replica examination using electron microscopy. The object of this work is to correlate the deformation behavior and the mechanical properties of materials hardened by particles.

Flow stress of polycrystals

The effect of grain size on the flow stress of polycrystals was reviewed. Models for the flow stress-grain size relationship were discussed with emphasis on microstructural parameters and texture. A number of experimental observations were reviewed critically and compared with model predictions. The conclusion is that many conflicting results can be explain if both grain boundary strengthening and texture strengthening are considered.

Deformation of composites

Tension-compression data measured at room-temperature for copper reinforced with tungsten fibres were analyzed in terms of the matrix flow stress and the matrix mean stress using a combination of the source-shortening concept and a mean field model. Each of the two matrix stresses is a linear superposition of an elastic term proportional to the applied stress and an inelastic term proportional to the unrelaxed inelastic strain in the matrix. The inelastic terms dominate at low fibre volume fractions (< 0.1) and this allows the overall hardening contribution from the mean stress to be separated from the flow stress contribution. For higher fibre contents the four hardening contributions are of comparable magnitude and the matrix flow stress contribution therefore can no longer be separated from the mean stress contribution. Instead it seems possible to separate the inelastic contributions, which are subject to plastic relaxation, from the elastic contributions.

Fatigue in copper

The combined effects of polycrystallinity and Al_2O_3 particles in the early stages of low amplitude fatigue of copper were studied. It was found that the rapid hardening stage is strongly affected both by polycrystallinity and particles. Transmission electron microscopy showed that the dislocation microstructure in the cyclically saturated Cu and Cu-Al_2O_3 polycrystals is modified at the grain boundaries, but it is only weakly affected by the particles. Work was initiated to study the effect of texture on the cyclic stress-strain curve of Cu polycrystals.

In collaboration with the Cavendish Laboratory, University of Cambridge, electron microscopy was used in a study of slip band formation in the dislocation microstructures produced in copper single crystals by cyclic straining at constant amplitudes of plastic shear. The structures were found to depend strongly upon the plastic strain amplitude: for $e_p = 0.5 \times 10^{-3}$ crystals which were cyclically saturated, or nearly so, contain a large

volume fraction (~ 0.5) of fibre-like veins; for $e_p = 3.1\ 10^{-3}$ the vein volume fraction is substantially lower (~ 0.2) and the veins are more plate-like; for $e_p = 6.3 \times 10^{-3}$ a cell structure was found. Ladder-like features were occasionally seen before saturation at $e_p = 3.1 \times 10^{-3}$. These observations together with the recorded stress-strain behaviour suggest that the fatigued crystals deform largely as composites of plastically non-deforming veins in an ideal plastic matrix.

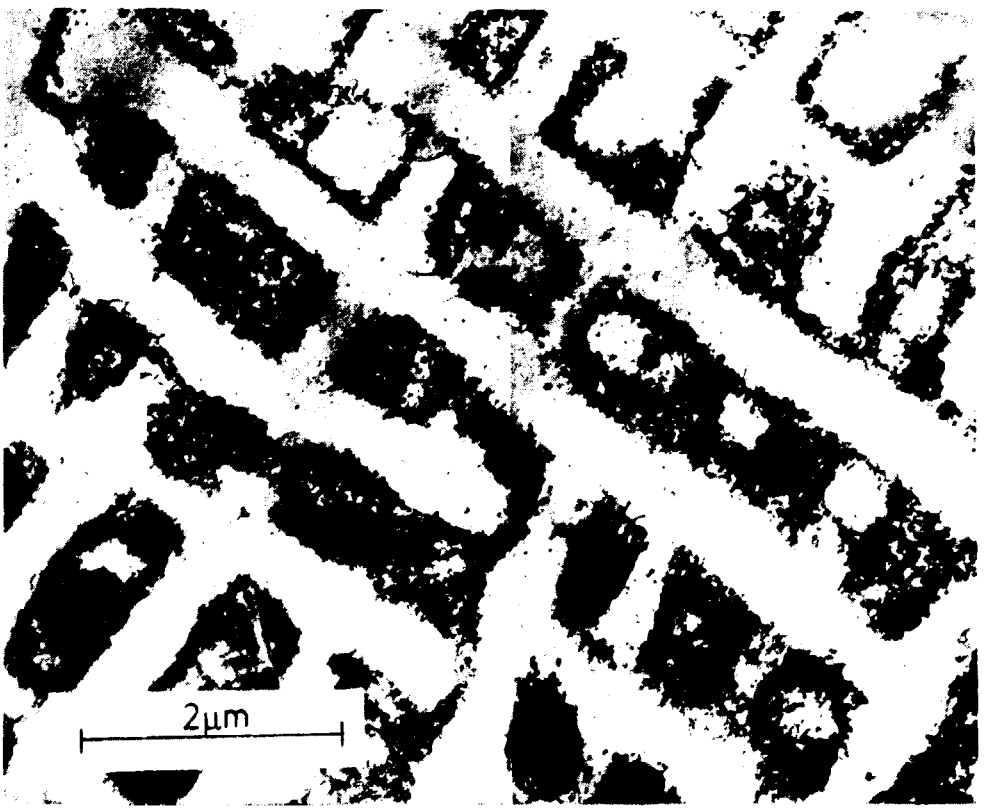

Fig. 3. Transmission electron micrograph showing a two-dimensional wall structure or 'labyrinth' structure in fine-grained pure copper (grain-size ~ 25 µm). Some of the rectangular clumps of dislocations contain areas free of dislocations. The specimen was subjected to 10185 cycles of tension-compression at a plastic strain amplitude of $\varepsilon_p = 10^{-3}$.

Creep in f.c.c. metals

The modified network recovery model for creep was further refined. The novel approach in this model is that sites for strong recovery are assumed to be created by the glide process so that the recovery rate becomes dependent on the the strain history. The recovery sites are formed by the reaction between dislocation of opposite sign on intersecting slip planes. In particular, the model was used to consider the course of the annealing of a dislocation network following a stress removal during creep.

Creep experiments were performed on Cu dispersion-hardened with Al_2O_3 and on Al dispersion-hardened with Al_2O_3.

Irradiation of high-purity aluminium with 600 MeV protons

(In collaboration with EIR/SIN, Würenlingen, Switzerland)

Annealed samples of high-purity aluminium (99.9999%) were irradiated with 600 MeV protons at the Swiss Institute for Nuclear Research (SIN) to different dose levels (up to 5 dpa) at temperatures in the range of 120-280°C. In order to evaluate the role of the grown-in microstructure (dislocations and their distribution) in the formation and growth of voids and bubbles some polygonized (10% cold-worked and annealed at 130°C for 24 hrs) specimens of the same aluminium were also irradiated.

TEM examination showed the presence of large cavities (voids) in specimens irradiated to all doses up to 5 dpa at irradiation temperatures of up to 140°C; at 170°C and beyond, no large cavities (voids) were observed. As reported earlier, the spatial distribution of these voids was found to be very heterogeneous; the presence of large cavities (voids) was restricted mainly to narrow bands along grain boundaries. At a dose level of 5 dpa, a high density ($> 10^{22}$ m^{-3}) of very small helium bubbles were observed in the grain interior of a specimen irradiated at 120°C. At higher irradiation temperatures helium

bubbles became visible at doses lower than 5 dpa. At all irradiation temperatures and doses, the helium bubbles at grain boundaries were larger in size and lower in density than those in the grain interior. TEM examination also showed that helium bubbles are formed preferentially at dislocation lines, dislocation networks and grain boundaries.

Irradiation of high purity aluminium with neutrons

High purity aluminium (the same material as used in the 600 MeV proton irradiations) was irradiated with fast neutrons

Fig. 4. Void distribution in polygonized high purity aluminium irradiated at 120°C to a fluence of 1×10^{24} n m^{-2}. The void density is enhanced in the centers of large cells while small cells contain no voids.

in the DR 3 reactor at Risø. The specimens, with well controlled microstructures, were irradiated to fluences between 2×10^{21} and 1×10^{24} n m^{-2} at 120°C and investigated by TEM. A void denuded zone is seen both at grain boundaries and at dislocation cell walls. Enhanced void formation and growth occurs in a zone extending up to 10 μm from grain boundaries in annealed material. In polygonized material, the presence of dislocation cell walls leads to cell size dependent void formation and growth; the swelling rate in the large cells is substantially higher than in the annealed material.

Void size and density distributions were studied further using the Risø small angle neutron scattering facility (SANS). Analysis of the scattering response from the void population produced at the highest fluence gave good correlation with conventional TEM analysis.

Radiation experiments on cold-worked copper

(In collaboration with the Metallurgy Division, AERE Harwell, U.K.)

The experimental work with high voltage electron microscope irradiation (1 MeV electrons) of cold worked copper was completed. For all degrees of cold work (10-90% reduction), all irradiation temperatures (250-450°C) and all doses (up to ~ 50 dpa) the substructure introduced by cold work basically survived the irradiation, but, of course, with significant recovery.

The effect of cold work on void swelling is an initial increase of swelling with increasing degree of cold work followed by a decrease with further increase in cold work. The initial increase can be rationalized in terms of the increase in dislocation density. The decrease in swelling with further increase in the degree of cold work, on the other hand, cannot be explained by a simple further increase in dislocation density. In order to explain the decrease one has to consider the real heterogeneous distribution of dislocations. Theoretical work along this line is in progress.

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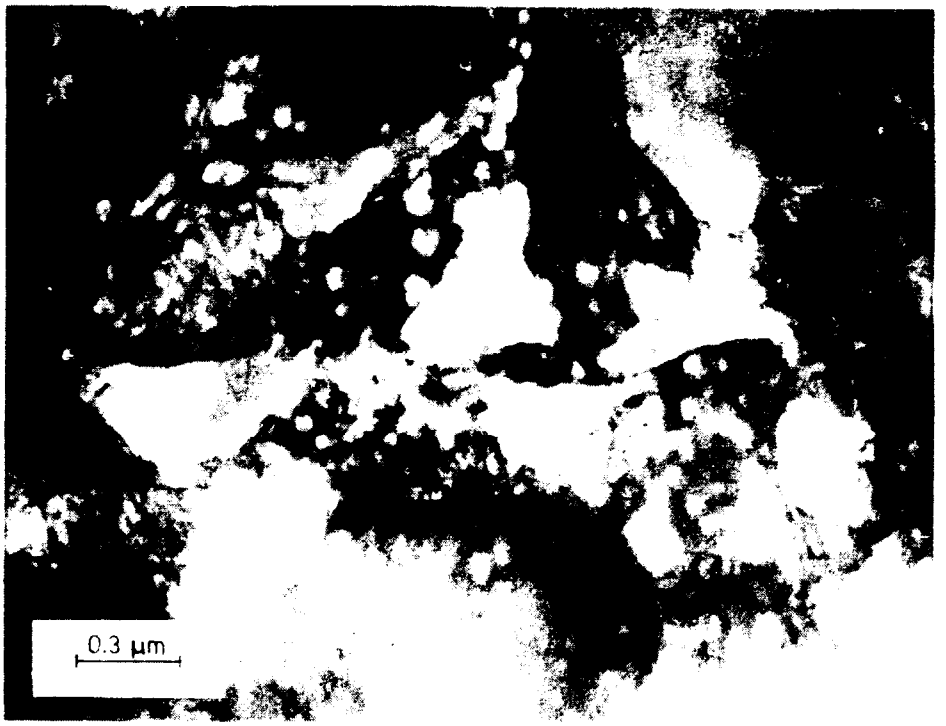


Fig. 5. Void swelling in cold-worked copper. The transmission electron micrograph shows voids formed by irradiation with 1 MeV electrons. The dislocation substructure introduced by cold-work has survived the irradiation but with significant recovery.

The aim of the work on copper is to investigate the effect of cold work on void swelling in a material without the structural complexity of materials like steel. Comparison of the present results with recent investigations on cold-worked steel confirm that the swelling behaviour of copper is relevant for that of steel.

Recrystallization and grain growth in particle containing materials

(In collaboration with the Department of Metallurgy and Materials Science, University of Cambridge).

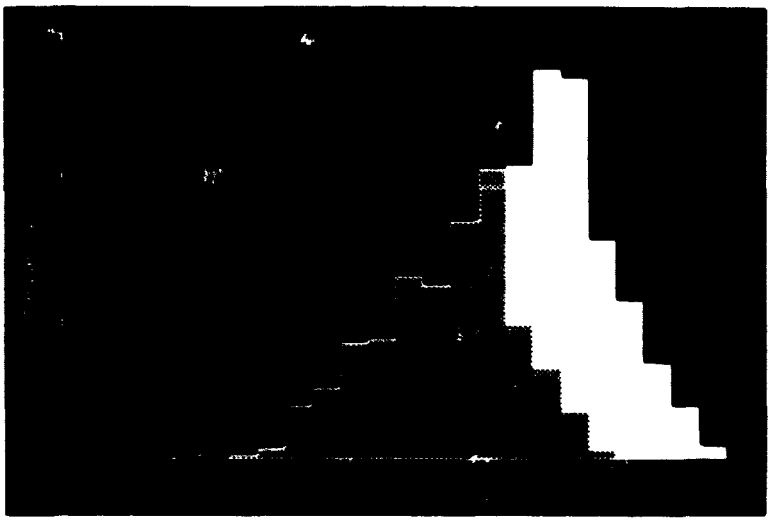
The grain growth after recrystallization was studied by quantitative light microscopy in metals containing a dispersion of small particles (diameter < 0.1 μm). It was found that the particles affect the grain size distribution strongly during grain growth. The grain size effect was related to phenomena such as abnormal grain growth and the occurrence of a limiting grain size. Figure 6 illustrates the grain size distribution before and after grain growth in black and white, respectively. The grey areas mark the overlap of the two distributions. The first part of the study was followed by detailed analyses of the interaction between high angle grain boundaries and particles, using transmission electron microscopic observations and channeling diffraction patterns.

Work was initiated to study migration of high angle grain boundaries in bi-crystals. Part of this work will be based on in-situ measurements using neutron diffraction techniques.

Recrystallization kinetics investigated by neutron diffraction

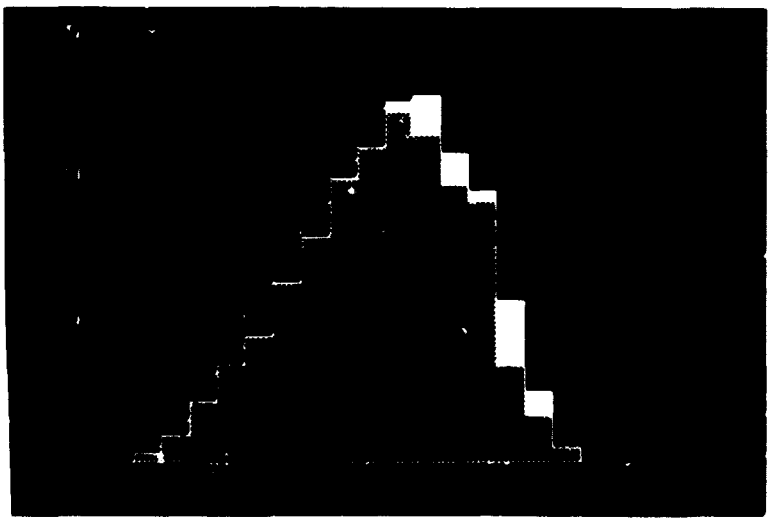
(In collaboration with the Physics Department, Risø)

The recrystallization process in pure copper rolled to 95% reduction was studied by in-situ texture measurements in a new fast neutron texture goniometer. The temporal evolution of specific texture components was followed during isothermal annealing, either by recording complete pole figures or by recording pole densities along 34° small-circle segments in the pole figure with the position-sensitive detector, keeping the sample orientation fixed. The latter method gives a time resolution of the order of seconds.



A

Fig. 6. The effect of Al_2O_3 particles on the grain growth in Al which was heat treated after recrystallization for 10 h at 873 K. (a) Al-Al_2O_3 material containing 0.16 10^{-2} volume percent Al_2O_3. This material showed normal grain growth under the conditions of the experiment. There was a loss of the smallest grains in the material balanced by growth of the larger grains. As abscissa is plotted the natural logarithm to the equivalent circle diameter (ln(ECD)). (b) Al-Al_2O_3 material containing 1.6 10^{-2} volume percent Al_2O_3. Grain growth is restricted by the presence of the particles and this material shows only a slight change in the distribution in the form of a slight narrowing. This change results from the loss of some of the smaller grains and some gain in the number of larger grains.



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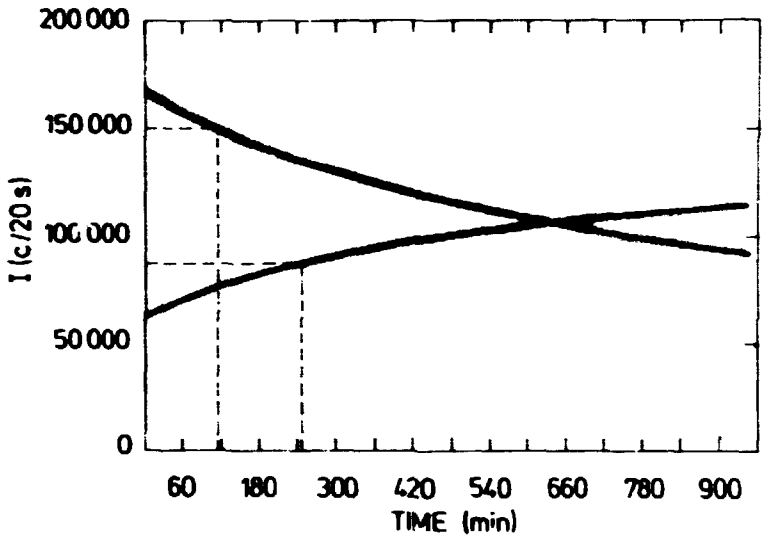


Fig. 7. Evolution in two texture components during recrystallization. One component represents the disappearing rolling texture, the other component represents the appearing recrystallization texture.

Fig. 7 shows the evolution in two texture components during the recrystallization process, one from the disappearing rolling texture, one from the appearing recrystallization texture. Formally all the results can be described by an Avrami equation with ζ close to 1. In an Avrami framework this would correspond to one-dimensional growth (needle-shaped recrystallized grains). In reality the recrystallized grains are approximately equiaxed. The explanation is that the kinetics are governed by nucleation and not by growth: each nucleus grows quickly to a certain size and then stops growing. This interpretation was confirmed by electron microscopy.

TECHNOLOGY AND MATERIALS DEVELOPMENT

Brazing and soldering

Contract work was continued on industrial applications of dip-brazing, vacuum brazing and ultrasonic soldering of aluminium as well as vacuum brazing of stainless steels and nickel alloys.

Fibre-reinforced plastics

Research and development on fibre reinforced plastics were continued in the following fields: fabrication technology, testing methods, mechanical properties and design and analysis.

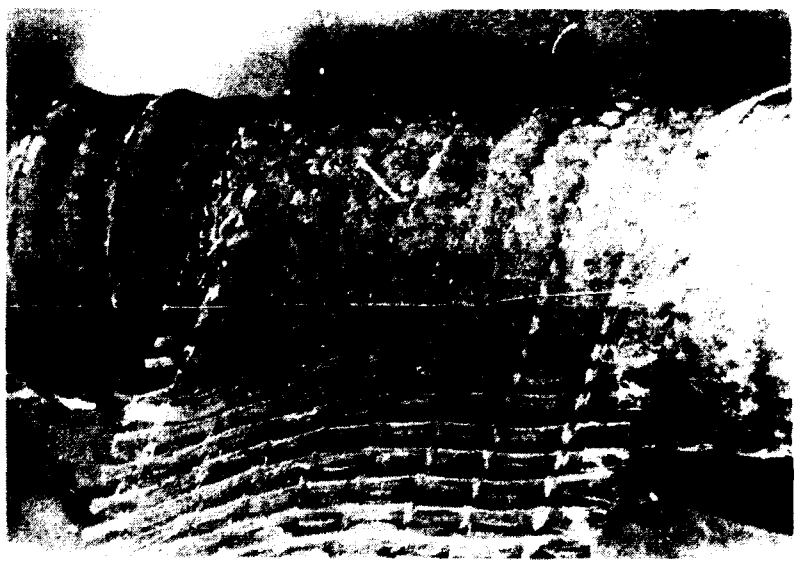


Fig. 8. Fabrication of fibre-reinforced plastic component by computer controlled tape winding.

Testing was carried out to determine stiffness and strength properties of filament wound cylinders. Special fixtures were designed to internally pressurize thin-walled small-diameter composite cylinders through rubber rods.

Joints between composite cylinders and metallic flanges were tested to evaluate the adequacy of the jointing method. The effect of the thickness of adhesive on the performance of the joints was also studied.

Long-term mechanical properties were studied both theoretically and experimentally. Previous work on fatigue damage mechanism maps for polymer matrix composites was extended to glass and glass-ceramic matrix composites. An approach to modelling of fatigue damage in composites was developed. Experimental work was concerned with measurements of stiffness loss under fatigue and with observations of failure modes.

Metal-Hydrogen Systems

The investigation of the properties of magnesium powder relevant to storage of hydrogen as magnesium hydride, MgH_2 was continued. The main object of the research is to study the long term behaviour of fine powders cycled (between metal and hydride) under conditions approaching those to be met in large scale application. From experiments in an automatic cycling rig it was concluded that the reactions undergo no significant changes within the first 150 cycles. Although the powder particles stick together forming a spongy conglomerate, neither the degree of reaction nor the reaction rate are reduced. Loss of capacity caused by irreversible reaction of Mg with oxygen or with water vapour present in the hydrogen is far below what might be expected if the reaction with the impurities was complete.

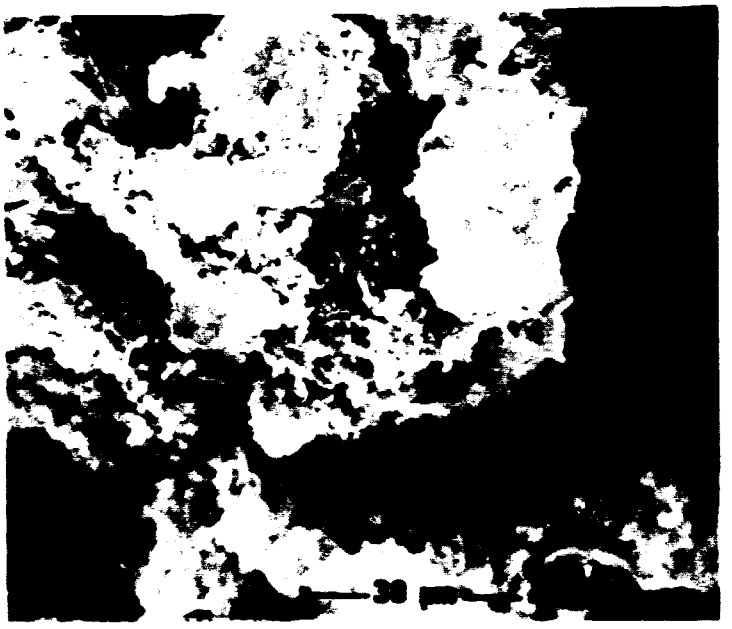


Fig. 9. Conglomeration of particles after 71 cycles of hydrogen absorption-desorption. The original particle size is less than 75 μm.

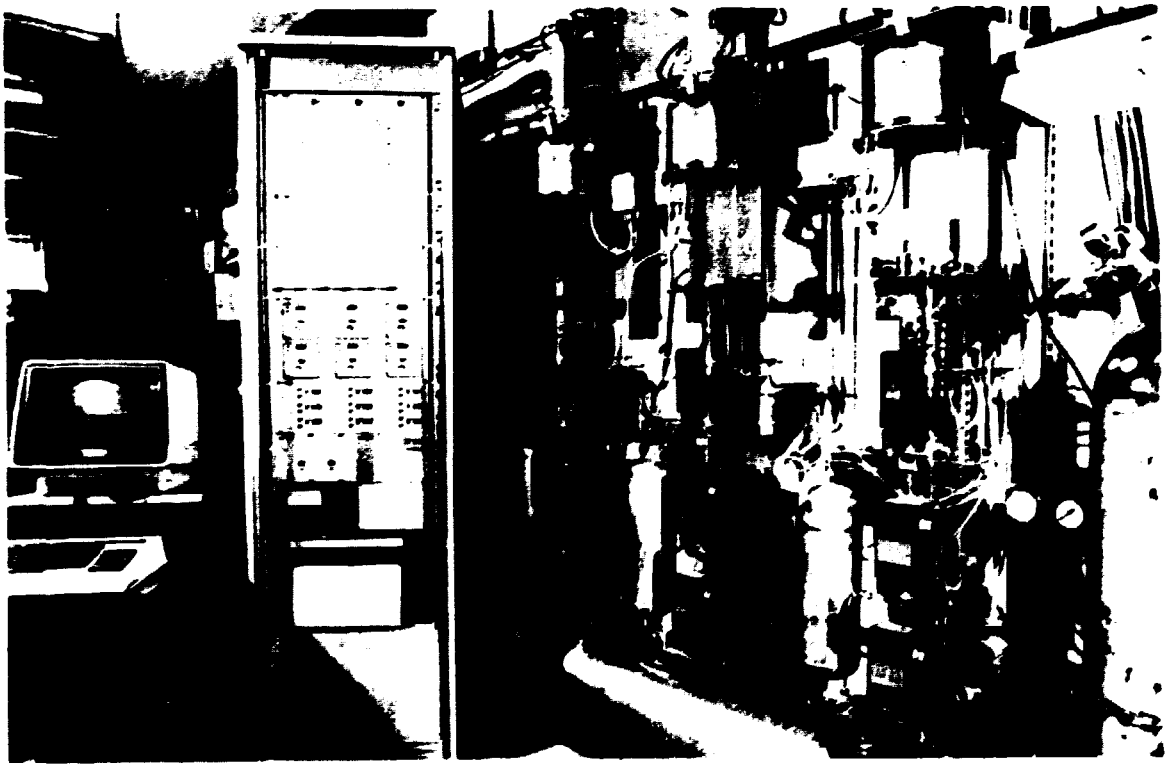


Fig. 10. Automatic facility for hydrogen absorption-desorption cycling. From left to right: data terminal, electronic control panel and three test lines.

Solid electrolytes for lithium batteries

(In collaboration with the Physics Department at Risø)

Basic studies and development and characterisation of ionically conducting materials for use in rechargeable lithium batteries were continued. In the battery-oriented work (sponsored by EEC and the Danish Ministry of Energy) emphasis was put on attempts to improve the ionic conductivity of LiI based composite electrolyte materials. Modifications of previous production methods resulted in a further increase in conductivity (a factor of 3).

Ternary lithium nitride compounds and lithium thiocyanate based mixtures were studied. A study of the high temperature conductor $LiBiO_2$ was completed. A number of cubic compounds were studied by a combination of conductivity-, specific heat-, and neutron scattering measurements in an attempt to find quantitative relations between the defect structure and the ionic conductivity. These materials comprise the heavily doped fluorites $Ba_{1-x}La_xF_{2+x}$, $Ba_{1-x}U_xF_{2+2x}$ and $Pb_{1-x}U_xF_{2+2x}$, and the high temperature α-phase of Li_2SO_4.

Basic studies of the heavily doped fluorite systems by quasi-elastic diffuse neutron scattering have shown the presence of high concentrations of defect clusters comprising one (U^{4+}) or two (La^{3+}) excess-charge cations, two interstitial fluorines for charge compensation and two relaxed fluorines. At lower temperatures a tendency towards ordering of these defect clusters in more extended aggregates was observed in $Ba_{1-x}La_xF_{2+x}$. The influence of coupling between the defect clusters was observed in the ionic conductivity measurements as an anomalous variation in the temperature dependence. The thermal generation of structural disorder in fluorites was studied by specific heat measurements. Whereas the thermally generated decoupling between the defect clusters in $Ba_{1-x}La_xF_{2+x}$ could not be detected in the appropriate temperature range

there are in general observations in the specific heat studies which indicate that thermally generated disordering takes place even in the heavily doped systems.

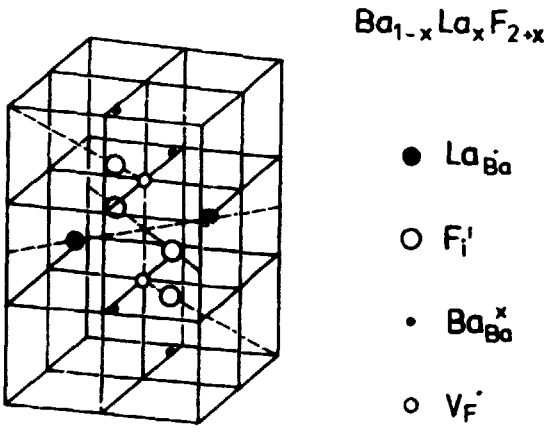


Fig. 11. Doped type of 222-cluster component of the defect structure in $Ba_{1-x}La_xF_{2+x}$ determined from diffuse quasi-elastic neutron scattering studies. The doped 222-clusters are composed of: 1) two interstitial fluorines ($F_i^{\cdot}$), for charge compensation of 2) two lanthanum ions on barium sites ($La_{Ba}^{\cdot}$), and 3) two relaxed ions (F_i'), creating two vacancies ($V_F^{\cdot}$).

Studies of the high temperature ionic-conducting α-phase of Li_2SO_4 were concentrated on structural aspects. In-situ growth of a single crystal on a neutron spectrometer was performed successfully and the neutron scattering results were used to show that the sulphate groups form rigid molecules which by rotation promote the lithium conduction.

Ionic thermo current experiments and Hebb-Wagner polarisation experiments were initiated in collaboration with The Solid State Department, State University of Utrecht, The Netherlands.

Lithium electrodes for non-reversible batteries

(In collaboration with A/S Hellesens)

The formation of a passivating LiCl-layer on lithium metal in thionylchloride electrolytes was followed in experiments by small signal ac-impedance measurements (frequency range: 5 Hz - 20 kHz) during periods of up to one year. These measurements revealed that the impedance, which is a function of the layer thickness, increased rapidly with time. In the first short period (20 days) the growth rate decreased, after which a linear increase with time was observed. The increase of the electrode impedance did not follow a sharp straight line but rather a linear band indicating that continous cracking and healing takes place in the layer. The equivalent circuit of the passivating electrode was determined. Indications were found that in addition to the growth in thickness of the LiCl-layer a decrease in porosity takes place in the inner part of the layer. The effect of various parameters such as mechanical handling, short term electrical loads and electrolyte composition and purity were studied.

Lithium-alloy anodes for reversible batteries

(In collaboration with Imperial College, London)

A new method for preparation of LiAl-anodes by electroplating lithium on aluminium foils was developed. By this method, anodes with a capacity of 15 coul/cm^2 can be obtained. The behaviour of these anodes in all solid state batteries is being tested.

Corrosion and erosion of steel in bicarbonate solution

Unalloyed and low-alloy steels develop a passivating oxide layer when exposed to concentrated, aerated hydrogen carbonate solutions. In stagnant solutions, this film is protective up to 250°C, while at 300°C a constant loss rate is observed.

In flowing slurries the electrochemical dissolution may be combined with mechanical erosion. However, no increase in loss rate is observed when the flow is increased from almost stagnant to some metres pr. second, neither at 200 nor at 250°C.

The sensitivity of the passive layer on steels in hydrogen carbonate solutions to attack by fluoride and chloride ions has been investigated under atmospheric conditions up to 90°C. Fluoride concentrations up to saturation and chloride up to at least 0.1% do not lead to pitting or other degradation of the passive layer. At 1% chloride, pitting can be induced at high potentials and moderate temperatures, while increasing the temperature to 60°C completely suppresses pitting.

FUEL ELEMENTS

The Danish water reactor fuels program continue to utilize the irradiation facilities in the OECD Halden Reactor in Norway and the DR 3 materials testing reactor at RISØ, as described briefly in the following. One of the Danish full elements irradiated in the Kahl BWR in West Germany will be taken to the RISØ hot cells for examination.

An internationally sponsored, three-year project, "The Risø Transient Fission Gas Release Project", has been launched in 1982. This is a follow-up program to "The Risø Fission Gas Project" that was executed in 1980-81.

Additional information on fuel performance becomes available as a result of international collaboration arrangements, i.e. the OECD Halden Reactor Project (Norway), the now completed "Demo-Ramp II" project (BWR fuel) and the "Super-Ramp" project (BWR and PWR fuel) at Studsvik (Sweden), Battelle's "High Burnup Effects Program", and the information exchange with the USNRC.

Danish fuel element irradiations in the Halden reactor

Irradiation of the three test fuel elements in the Halden reactor (Norway) was continued. They have now reached the following estimated burnups (average assembly, after correction for fuel depletion):

IFA No.	165	201	202
MWD/tU	41000	39400	35600

UO_2-Zr irradiations at Risø

Standard fuel pins currently under irradiation in the DR 3 reactor have reached max. burnup levels of 56000 and 54000 MWD/tU for BWR and PWR type fuel, respectively. The irradiation facilities are also used for testing of LOWI duplex fuel (see below) and for the transient tests with high-burnup fuel performed in the international fission gas projects.

Two PWR-type fuel pins, previously irradiated to 32000 MWD/tU, were taken from 160 to 370 W/cm and held for 24 hours. The resulting fission gas release and other hot cell measurements will be used in a "blind problem" exercise organized by IAEA for code comparison purposes.

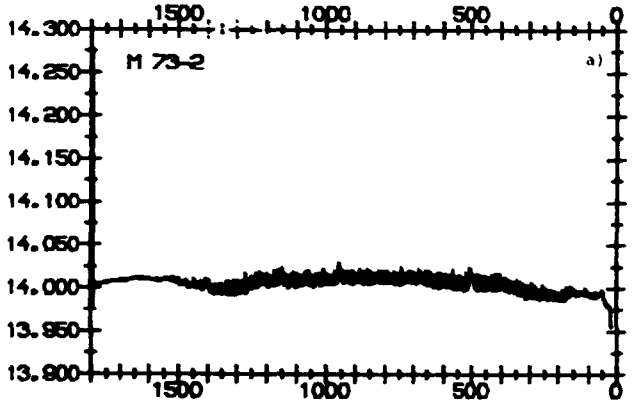
LOWI duplex fuel

The Danish duplex pellet LOWI (see for instance RISØ-R-340 and 354) is being irradiated in several tests in DR 3. The leading experiment has a central thermocouple still operating at a burnup of 38000 MWD/tU.

In a joint study by UKAEA, BNFL, HV and RISØ, performance calculations have been made for duplex fuel in a 17×17 PWR. The expected significant improvement in power ramp performance over standard fuel was found. Cost-benefit calculations show an increase in total fuel cycle costs of 2-5% for LOWI fuel. This extra cost can be traded off by the gain of 25-75 hours/year of full power operation if operational restrictions on ramp rates are removed.

Development of equipment and methods

Pressure transducers have been developed that can be mounted in the hot cells on irradiated fuel segments with special welding techniques. This will be utilized in transient tests within the new fission gas project described below. During these tests, internal pin gas pressure, pin power and other experimental



a) Variation of average diameter along the full pin length. The plot represents 10^6 measurements. Vertical scale 7 µm/mm.

b) Detailed plot of measurement a) in 200 mm axial interval. Vertical scale 1.4 µm/mm.

c) Maximum and minimum diameter variations in the same axial interval as above. Vertical scale 7 µm/mm.

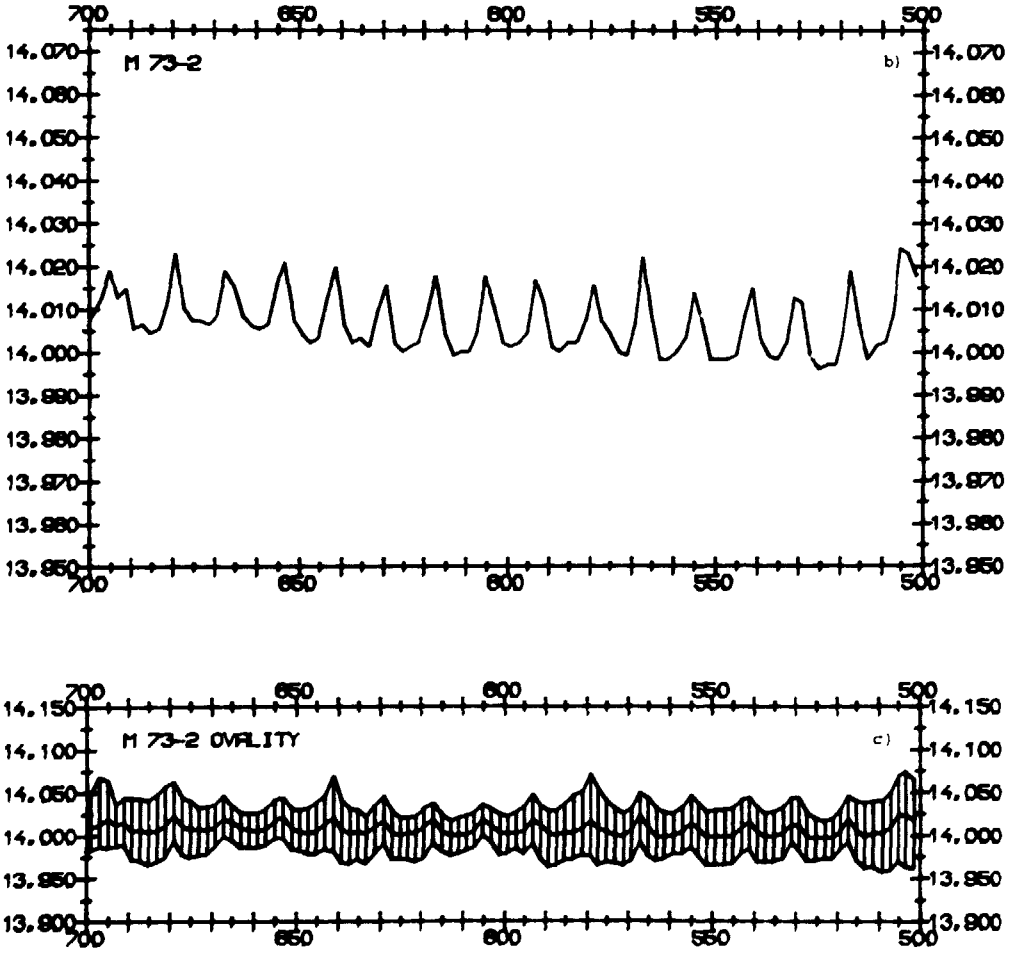


Fig. 12. Hot cell measurement of axial diameter variations of a 1800 mm long irradiated fuel pin.

conditions will be monitored continously with automatic data acquisition equipment.

Computer-controlled, non-destructive measuring equipment has been developed and commissioned for fuel pin profilometry, gamma measurements and eddy-current testing. The measuring systems permit the highest accuracies obtainable under hot cell conditions; they are linked to automatic data acquisition equipment. Figure 12 present examples of various diameter measurements on a fuel pin.

The Risø Transient Fission Gas Release Project

There is a general interest in data on the fission gas release from high-burnup fuel, especially in transients late in life, and there are very little data available to give an indication of the function of hold time at the transient power.

On this background, it has been possible to launch in 1982 a new international program to study the kinetics of fission gas release at high burnup. The project period is three years and the sponsors are fuel suppliers, utility organizations, authorities and research organizations from Europe, United States and Japan.

The project will utilize fuel partly from one of the Danish Halden assemblies and partly from a BWR power reactor. This fuel will be refabricated in the hot cells and mounted with pressure transducers for subsequent transient testing in DR 3. Important test parameters are: transient power (up to 450-500 W/cm), burnup (15000-40000 MWD/tU) and fill gas (Xe, He of various pressures). There will be at least 17 transient tests. The Halden assembly has been received in the Risø hot cells and the non-destructive examination is well under way, as well as radiochemical burnup determination for verification of the Halden irradiation power history.

PARTICIPATION IN INTERNATIONAL COLLABORATION

The department is engaged in the following types of international collaboration: joint technical projects, committee work, reception of research fellows, and technical and scientific meetings. The cooperation programme on irradiation damage between the department and the Kharkov Physical-Technical Institute was continued.

The department was represented on the following committees:

The Information Exchange Group under the European Space Agency on Carbon Fibre Reinforced Plastics,

The Halden Programme Group,

The IAEA International Working Groups on "Reliability of Reactor Pressure Components" and "Water Reactor Fuel Performance and Technology",

The Over-Ramp, Super-Ramp and Demo-Ramp Project Committees, The Project Committee on the Batelle HBEP-Programme, The OECD/EEC Nuclear Agency's Committee on the safety of Nuclear Installations (NEA-CSNI), Working Group on Safety Aspects of Steel Components in Nuclear Installations,

The COST 501 Committee on Materials for Energy Conversion using Fossil Fuels,

The EEC Advisory Committees for Programme Management: "Plutonium and Transuranium Elements" and "High Temperature Materials",

The European Coal and Steel Community, Executive Committee No. 5: Failure Mechanisms and Design,

The Euratom Neutron Radiography Working Group,

The Council of the International Confederation of Thermal Analysis,

The Nordic Committee for Thermal Analysis,

and in the Technical Commission of the International Institute of Welding, Commission I, "Gas Welding and Allied Processes", Subcommission A, "Brazing and Surfacing".

EDUCATION AND TRAINING

N. Hansen and K. Rørbo gave regular lectures on materials science to students at the Danish Academy of Engineering. O. Toft Sørensen, B. Vigeholm, A.S. Pedersen and B.N. Singh lectured on physical materials science to students at the Technical University of Denmark. N. Hansen, T. Leffers and H. Lilholdt acted as external examiners at examinations for the Technical University of Denmark, and O. Toft Sørensen acted as external examiner at examinations for the Technical University of Norway, Trondheim.

Three scolarship holders from Egypt worked in the Department on projects in the field of texture analysis and materials testing, and in the field of solid state ion conductors, respectively.

One scolarship holder from India worked in the Department on projects in the field of fracture mechanics study of irradiated pressure vessel steels.

Post-graduate projects

One post-graduate student from the Technical University of Denmark worked in the department on the following projects in preparation for her licentiate(Ph.D.) thesis:

D. Juul Jensen	Investigation of recrystallization kinetics by neutron diffraction texture measurements.

Degrees conferred

The Technical University of Denmark conferred the degree of lic.techn. (Ph.D.) on A. Koplev (early 1983).

PUBLICATIONS

Metallurgi og Materialeforskning - Metallurgiafdelingen 1957-1982. (Metallurgy and Materials Research - The Metallurgy Department 1957-1982).

(Risø National Laboratory, Roskilde, 1982) 32 pp.

A resume of the materials research carried out in the Metallurgy Department from 1957 to 1982.

Metallurgy Department Progress Report for the Period 1 January to 31 December 1981.

Risø-R-473 (1982) 79 pp.

The activities of the Metallurgy Department at Risø during 1981 are described. The work is presented in three chapters: General Materials Research, Technology and Materials Development, Fuel Elements. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1981 is included.

Standardization in the field of Neutron Radiography of Nuclear Fuel.

J.C. Domanus, In: Proceedings of the 4th International Conference on Non-Destructive Evaluation in Nuclear Industry, vol. 3, Lindau, Germany, 25-27 May, 1981. (Deutsche Gesellschaft für Zerstörungsfreie Prüfung, Berlin, 1981) 461-466.

Neutron radiography is mostly used in the pre- and especially post-irradiation control of nuclear fuel elements. It was felt that as in other fields of industrial radiography standard methods and procedures to control the quality of the radiographic image are needed. Standard reference radiographs showing typical defects revealed by neutron radiography are also necessary. Therefore, a working group was formed at Euratom to deal with those matters within EEC. Progress of work obtained after almost three years of activity of the group is reported.

Travaux Euratome sur Défaus Étalons et Mesures Dimensionelles dans la Neutronographie des Combustibles Nucleaires. (Work in Euratom on Standard Defects and Dimensional Measurements in Neutron Radiography of Nuclear Fuel).

J.C. Domanus, In: Recueil des Communications (Gathering Communications). Journées Nationales sur les Essais Non Destructifs, Paris, 26-29 January, 1982. (Comité Francais des Essais Non Destructifs, Paris, 1982) 72-83.
Also published as Risø-M-2318.

In 1979 a working group on neutron radiography was formed at Euratom. The purpose of this group is the standardization of neutron radiographic methods in the field of nuclear fuel. First priority was given to the development of image quality indicators and standard objects for the determination of accuracy of dimensional measurements from neutron radiographs. For that purpose beam purity and sensitivity indicators as well as a calibration fuel pin were designed and fabricated at Risø. All the Euratom neutron radiography centers have received the above items for comparative neutron radiography. The measuring results obtained, using various measuring apparatus, will form the basis to formulate conclusions about the best measuring methods and instruments to be used in that field.

Accurate Three-Dimensional Characterisation of Ultrasonic Sound Fields (By Computer Controlled Rotational Scanning).

H.E. Gundtoft and T. Nielsen, Materials Evaluation 40 (1) (1982) 78-83.

A rotational scanning system has recently been developed at Risø National Laboratory. It allows sound fields from ultrasonic transducers to be examined in three dimensions. Using different calculation and plotting programs, any section in the sound field can be plotted. Results from examination of transducers for automatic inspection are presented.

Computerized Hydraulic Scanning System for Quantitative Non-Destructive Examination.

H.E. Gundtoft, In: Proceedings of the 10th World Conference on Non-Destructive Testing, Moscow, 20-28 August, 1982. 178-186. (Also in Risø-M-2331).

A hydraulic scanning system with five degrees of freedom is described. It is primarily designed as a universal system for fast and accurate ultrasonic inspection of materials for their internal variation in properties. The whole system is controlled by a minicomputer which also is used for evaluating and presenting of the results of the inspection.

The Strain and Grain Size Dependence of the Flow Stress of Copper.

N. Hansen and B. Ralph, Acta metall. 30 (1982) 411-417.

Tensile stress strain data for 99.999% copper at room and liquid nitrogen temperature as a function of grain size are presented together with some microstructural observations made by transmission electron microscopy. It is shown that the flow stress data, at constant strain may be expressed in terms of a Hall-Petch relationship. At low strains an inhomogeneous distribution of dislocations is seen whilst at higher strains (0.1-0.2) a more regular cell structure begins to develop. This tends to have a minimum size near to grain boundaries. These microstructural observations are correlated with the mechanical test data.

Strengthening Mechanisms in Dispersion Hardened Copper Polycrystals.

N. Hansen and B. Ralph, In: Strength of Metals and Alloys. Proceedings of the 6th International Conference on the Strength of Metals and Alloys, Melbourne, 16-20 August 1982, Vol. 1. Edited by R.C. Gifkins (Pergamon Press, Oxford, 1982) 295-300.

Fine-grain polycrystals of pure copper and copper containing a dispersion of alumina particles have been mechanically tested over a range of tensile strain. Transmission electron microscopy has been used to characterize the deformation substructures in both series of samples (with and without alumina particles) after tensile strains of 0.05, 0.10 and 0.20. Dislocation densities have been measured semi-quantitatively and these data have been used in the interpretation of the mechanical property results using a forest model. The structural observations indicate that there is a strength contribution from the particles in or near the grain boundaries which relates well with the flow stress measurements.

Microstructures and Deformation Mechanisms in Polycrystalline Aluminium.

N. Hansen and B. Bay, In: Strength of Metals and Alloys. Proceedings of the 6th International Conference on the Strength of Metals and Alloys, Melbourne, 16-20 August 1982, Vol. 1. Edited by R.C. Gifkins (Pergamon Press, Oxford, 1982) 401-406.

The microstructures resulting from cold-rolling of polycrystalline 99.998% aluminium have been studied by transmission electron microscopy. The material was produced in coarse-grained and fine-grained states and reduced by cold-rolling 2 to 30%. The studies of the bulk behavior were supplemented by replica examination by electron microscopy of surface displacements during deformation. The bulk and the surface observations were correlated; special emphasis was placed on the structure in the grain boundary region. Finally the role of grain boundaries is discussed with respect to the deformation structures observed.

Recovery and Recrystallization of Particle Containing Materials.

N. Hansen and A.R. Jones, In: Les Traitements Thermomecaniques. Proceedings of the 24 ème Colloque de Métallurgie, Saclay, June, 1981. (Institut National des Sciences et Techniques Nucleaires) 95-110.

The recovery and recrystallization of metals containing a dispersion of small particles (diameter < 0.1 μm) is reviewed with special emphasis on the behaviour of aluminium-aluminium oxide alloys. It is shown that the retardation of recovery and recrystallization caused by the presence of small particles involves pinning of both low and high angle boundaries, which effects subgrain growth, growth of recrystallizing grains and grain growth subsequent to recrystallization. It is finally demonstrated that the shape, the size and the size distribution of grains in the recrystallized state and after grain growth is a function of size, distribution and volume fraction of the dispersed particles.

EF's energiforskning. (Energy Research in the EEC).

N. Hansen, Berlingske Tidendes kronik 16 April 1982.

A short resume and a discussion of the energy research within EF.

Plastisk deformation og rekrystallisation af aluminium af kommerciel renhed. (Plastic Deformation and Recrystallization of Aluminium of commercial Purity).

B. Bay and N. Hansen, In: DIALOG 25 år, 4-82 (DIALOG 25 years, 4-82). Artikler om maskin og produktionsteknik (Danmarks Ingeniørakademi, Maskinafdelingen, Lyngby, 1982) 21-33.

The structural processes taking place during cold work and recrystallisation of aluminium commercial purity are described.

Neutron Scattering Studies of the Ionic Conductor LiI D_2O.

N. Hessel Andersen, J.K. Kjems and F.W. Poulsen, Physica Scripta 25 (1982) 780-784.

The abstract appeared in the previous progress reports p. 68.

Interface Boundary Structure during the Growth of Gold Films on Platinum at High Temperature.

V.M. Ijevlev, K.S. Solovjev, S.B. Kushev and A. Horsewell, Philos. Mag. A. 45 (1982) 647-656.

Transmission electron microscopy observations of the interfacial structures formed between epitaxial gold overgrowths on (001) and (111) platinum substrates are reported. Both continuous layer and island structures, each with associated misfit dislocations, could be seen. Structural changes resulting from in situ heating indicate that both layer-by-layer and three-dimensional island mechanisms of Au and Pt occur simultaneously.

Microstructural Study of Titanium Carbide Coating on Cemented Carbide.

S. Vuorinen and A. Horsewell, J. Mater. Sci. 17 (1982) 589-594.

Titanium carbide coating layers on cemented carbide substrates have been investigated by transmission electron microscopy. Microstructural variations within the typically 5 μm thick chemical vapour deposited TiC coatings were found to vary with deposit thickness such that a layer structure could be delineated. Close to the interface further microstructural inhomogeneities were observed, there being a clear dependence of TiC deposition mechanism on the chemical and crystallographic nature of the upper layers of the multiphase substrate.

Neutron Diffraction Texture Measurements as a Tool for the Investigation of Recrystallization Kinetics.

D. Juul Jensen, N. Hansen, J. Kjems and T. Leffers, In: Proceedings of the Sixth International Conference on Textures of Materials, Tokyo, 28 September - 3 October 1981, Vol. 2 Edited by S. Nagashima (The Iron and Steel Institute of Japan, Tokyo, 1982) 1179-1188.

The abstract appeared in the previous progress report p. 69.

The Risø Fission Gas Project - An Overview.
P. Knudsen, In: Proceedings of the ANS Topical Meeting on LWR Extended Burnup - Fuel Performance and Utilization, Williamsburg, Virginia, 4-8 April 1982, Vol. 2. (American Nuclear Society, Virginia, 1982) 6/67-6/74.

The Risø Fission Gas Project has provided experimental data on fission gas release from high-burnup water reactor fuel. The data are well-characterized with respect to pre-irradiation measurement, irradiation and post-irradiation examination, thus enabling their use in fuel performance code validation.

The experimental data were obtained with 12 Zircaloy clad UO_2 pellet fuel pins, irradiated in a test assembly to an average of 32,000 MWD/tU. Most of the fuel pins were submitted to short-term reirradiations at increased power levels ("bump testing") in a test reactor, in order to simulate postulated power increases late in life. The bump tests covered a range of bump terminal levels of 320-462 W/cm (peak pellet), mostly with a hold time of 24 h. Extensive hot-cell examinations were performed of base-irradiated and bump-tested fuel pins.

The fission gas release resulting from the bump testing was in the range 0-16%, increasing with peak pellet levels above 400 W/cm. Local fission gas releases were determined from retained gas measurements on pellet size samples. Release of fission product cesium as a function of local bump terminal level resembled the local fission gas release. The gas release measurements were corroborated by extensive ceramographic examinations and pore size analysis.

The International Overramp Project at Studsvik.

T.E. Hollowell, P. Knudsen and H. Mogard, In: Proceedings of the ANS Topical Meeting on LWR Extended Burnup - Fuel Performance and Utilization, Williamsburg, Virginia, 4-8 April 1982, Vol.1. American Nuclear Society, Virginia, 1982) 4/5-4/17.

A total of thirty-nine PWR design fuel rods have been ramp tested under fast power increase (100 W/cm min) in the Studsvik R2 test reactor after base irradiations in the Obrigheim and BR-3 power reactors. Burnup levels tested ranged from 12 to 31 MWd/kg U.

Failure thresholds have been established within particular groups of rods having nearly identical design and base irradiation history. The failure threshold has a lower value of approximately 420 W/cm at burnups around 25 MWd/kg U. Differences in design and operating parameters such as pellet-cladding gap, burnup, helium pre-pressurization level, enrichment, clad wall thickness, and base irradiation history have provided differences in observed rod performance. The location of the lower failure threshold coincides with corresponding findings reported from other LWR fuel test programs.

Non-destructive and destructive PIE examinations have provided a useful data set on well characterized rods. The data generated includes both steady state and transient performance characteristics over a significant range of design and operating conditions. Such a data base is especially useful for model verification efforts.

The program, which is cosponsored by 12 separate organizations and managed by Studsvik Energiteknik AB, Sweden, started in 1977 and was concluded in 1981.

Gitterfejl i metals atomstruktur får metallet til at bøje. (Lattice Defects in the Atomic Structure of Metals cause the Metal to Bend).

T. Leffers, Forskningen og Samfundet 8(8) (1982) 10-13.

The different types of lattice defects that break the regularity of the atomic arrangement in crystalline solids are described, and the decisive influence of the lattice defects on material properties are discussed. It is stated that the demand for improved properties makes it increasingly necessary to include the concept of lattice defects in materials technology (and not only in materials science).

Talmystikken er ikke spor mystisk. (The Mystery of the figures is not in the least mysterious).

T. Leffers, Ingeniøren 8 (27) (1982) 6.

It is explained why the first digits in random numbers are not evenly distributed (the distribution is approximately logarithmic with 1 being by far the most common first digit). For numbers given in arbitrary (man made) units it can easily be demonstrated that the logarithmic distribution is the only natural distribution. Most other numbers are derived from a count starting at 1, and it is demonstrated that they will also have a distribution of the first digit close to the logarithmic distribution.

The {111} Rolling Texture Component in Brass and its Relation to the Formation of the Brass-Type Texture.

T. Leffers, In: Proceedings of the Sixth International Conference on Textures of Materials, Tokyo, 28 September - 3 October 1981, Vol. 1. Edited by S. Nagashima (The Iron and Steel Institute of Japan, Tokyo, 1982) 385-395.

The abstract appeared in the previous progress report p. 70.

The Strength of Polycrystals.

T. Leffers and O.B. Pedersen, In: Strength of Metals and Alloys. Proceedings of the 6th International Conference on the Strength of Metals and Alloys, Melbourne, 16-20 August 1982, Vol. 1. Edited by R.C. Gifkins (Pergamon Press, Oxford, 1982) 75-82.

The strength of polycrystals and its subdivision into different components is discussed. Special attention is paid to the contribution of internal stresses and the contribution of stored dislocations. Bauschinger experiments for the investigation of the former contribution are suggested and preliminary results quoted. For the latter contribution new upper-bound expressions are derived, and their relation to geometrically necessary dislocations is discussed.

Avancerede Plastkompositter. (Advanced Fibre Reinforced Plastics).

H. Lilholt, In: Kompositmaterialer (Composite Materials). Møde om Fremtidens Konstruktionsmaterialer, Tåstrup and Århus, 30 November - 1 December 1982. (Teknologirådets kompositmaterialeudvalg, København, 1982) 33-44.

The mechanical properties of fibre reinforced composite materials are presented.

Relations between Matrix and Composite Creep Behaviour.

H. Lilholt, In: Fatigue and Creep of Composite Materials, Proceedings of the 3rd Risø International Symposium on Metallurgy and Materials Science, Risø, 6-10 September 1982. Edited by H. Lilholt and R. Talreja (Risø National Laboratory, Roskilde, 1982) 62-76.

The creep behaviour of fibre-reinforced composite materials is presented, and the relation to the creep of the (metal) matrix is evaluated. The strength contributions for creep are discussed, and an example of the operative strength contributions is given.

Fatigue and Creep of Composite Materials.

H. Lilholt and R. Talreja (editors), Proceedings of the 3rd Risø International Symposium on Metallurgy and Materials Science, Risø, 6-10 September 1982. (Risø National Laboratory, Roskilde, 1982) 342 pp.

The proceedings of the 3rd Risø symposium contain 11 invited and 25 contributed papers in the field of the science of fatigue and creep of composite materials.

Materialevalg til et uranudvindingsanlæg. (Selection of Materials for a Uranium Extraction Plant).

T.S. Nielsen, In: Valg af Materialer (Selection of Materials). Dansk Metallurgisk Selskabs Vintermøde, Helsingør, 6-8 January 1982. Edited by E.W. Langer and T.S. Nielsen (Dansk Metallurgisk Selskab, Lyngby, 1982) 179-193.

Selection of Materials for a Uranium Extraction Plant. A pilot plant for carbonate pressure leaching of Kvanefjeld ore has been erected at Risø. The process is outlined with a view to the different environments occurring in the plant. Degradation of construction materials in these environments is reviewed and the resulting materials selection presented, together with preliminary results from a laboratory testing programme. (In Danish).

The Cyclic Stress-Strain Curve of Polycrystals.

O.B. Pedersen, K.V. Rasmussen, and A.T. Winter, Acta Metall. 30 (1982) 57-62.

The internal stresses implied by the Sachs model are estimated for individual PSBs at low plastic strain amplitudes and for homogeneously sheared grains at higher plastic strain amplitudes. The analysis shows that the Sachs model can account semi-quantitatively for experimentally measured cyclic stress-strain curves for copper. A similar approximative analysis of the Taylor model cannot account for the data. An interesting feature of the Sachs model is that, although it is assumed that the flow condition is entirely controlled by the PSBs, the predicted cyclic stress-strain curve displays an upward slope at high plastic strain amplitudes.

Fatigue Hardening and Nucleation of Persistent Slip Bands in Copper.

O.B. Pedersen and A.T. Winter, Acta Metall. 30 (1982) 711-718.

A study of fatigue hardening in single crystals of pure copper shows that, before saturation, stress-strain loops can display workhardening rates of about a third of the elastic shear modulus. These rates exceed tensile workhardening rates by roughly two orders of magnitude. This suggests that there is a large volume fraction of obstacles to plastic flow which are essentially non-deformable and give rise to inclusion stresses of considerable magnitude. The much lower hardening rates in cycles after saturation when persistent slip bands have formed suggest a lower volume fraction of obstacles, as is observed by transmission electron microscopy. A simple composite model involving an inclusion stress, a bowing stress and a passing stress accounts for the workhardening rates semi-quantitatively in terms of observed dislocation microstructures. Possible implications for polycrystals are considered.

Anvendelse af højtemperaturlegeringer i katalytiske reformere. (Application of High Temperature Alloys in Catalytic Reformers).

K. Rørbo, In: Valg af Materialer (Selection of Materials). Dansk Metallurgisk Selskabs Vintermøde, Helsingør, 6-8 January 1982. Edited by E.W. Langer and T.S. Nielsen (Dansk Metallurgisk Selskab, Lyngby, 1982) 127-140.

The conditions under which catalyst tubes in steam reformes are operating and the properties of the appropriate materials (centrifugally cast austenitic FeCrNi alloys as HK40, IN519 and 25 Cr/35 Ni) are discussed. The development of microstructure during operation and problems with creep, oxidation and carburization are reviewed. Finally the use of alloy 800H for outlet hairpins is mentioned.

Formation of Cavities at and away from Grain Boundaries During 600 MeV Proton Irradiation.

B.N. Singh, T. Leffers, W.V. Green and S.L. Green, J. Nucl. Mater. 105 (1982) 1-10.

High-purity aluminium (99.9999%) was irradiated with 600 MeV protons at the Swiss Institute for Nuclear Research (SIN) with a damage rate of 3.5×10^{-6} dpa/s. Irradiation with 600 MeV protons produces helium, hydrogen, and other impurities through mutational reactions. The irradiation experiments were carried out at ~ 120°C (~ 0.42 T_m, where T_m is the melting temperature in K). Transmission electron microscopy on specimens irradiated to 0.2 and 0.6 dpa has shown the presence of (a) cavity-denuded zones (CDZ) along grain boundaries, (b) cavity-containing zones (CCZ) adjacent to the CDZ and (c) regions beyond the CCZ containing a very low density of cavities. At the dose level of 2 dpa, a dense population of very small cavities is resolved on the grain boundaries and also in their immediate vicinity (in the CDZ). Furthermore, at the dose levels of 0.6 and 2 dpa, a well defined dual size distribution of cavities is observed in the CCZ. The results are discussed in terms of agglomeration of helium atoms which are considered, during irradiation, to diffuse mainly via vacancies.

Damage Models for Fatigue of Composite Materials.

R. Talreja, In: Fatigue and Creep of Composite Materials, Proceedings of the 3rd Risø International Symposium on Metallurgy and Materials Science, Risø, 6-10 September 1982. Edited by H. Lilholt and R. Talreja (Risø National Laboratory, Roskilde, 1982) 137-153.

Mechanisms of damage in fibres, matrix and interface caused by tensile fatigue in unidirectional composites are described. Composites having brittle (e.g. glass and graphite) fibres in ductile (polymer) or brittle (e.g. glass and glass-ceramics) matrices are considered. A systematic scheme for evaluating the fatigue performance of composites is presented. This scheme is shown to reveal certain characteristics of the composite fatigue behaviour that are not easily seen by plotting the usual S - N curves. Based on the knowledge of the damage mechanisms, a few models for predicting the fatigue behaviour of composites are discussed. The models considered here are the statistical models for fibre damage and the continuum mechanics models for matrix and interfacial damage.

Formation and Decomposition of Magnesium Hydride

B. Vigeholm, J. Kjøller, B. Larsen and A. Schrøder Pedersen

J. Less-Common Metals 89, No. 1 (1982) 135-144.

The absorption of hydrogen in magnesium (purity, 99.8% - 99.94%) was studied in the temperature range 260 - 425°C and at pressures from the equilibrium value to 2 MPa above equilibrium. At constant temperature the absorption rate depends on the pressure whereas total absorption is attained in approximately the same time regardless of the pressure. The final composition is very close to stoichiometric MgH_2 except at the lowest temperatures and highest pressures investigated when the reaction becomes extremely slow or ceases completely at 80% - 90% of the stoichiometric composition. Accurate determination of the relative molar enthalpy gives a value of -70 kJ $(mol\ H_2)^{-1}$. No hysteresis in the ordinary sense was observed, but although no change in the plateau pressure occurred desorption of from 5%-15% of the remaining hydrogen required almost zero pressure. The actual value appears to be dependent on the material.

Hydrogen Sorption Performance of Pure Magnesium During Continued Cycling.

B. Vigeholm, J. Kjøller, B. Larsen and A. Schrøder Pedersen,

In: Hydrogen Energy Progress IV. Proceedings of the 4th World Hydrogen Energy Conference, California, 13-17 June, 1982. Edited by T.N. Veziroglu, W.D. van Vorst and J.H. Kelly (Pergamon Press, 1982) 1227-1238.

Preliminary investigations of the hydrogen absorption - desorption by commercially pure magnesium powder under continuous operation show little or no reduction in hydrogen capacity up to 70 cycles and high temperature exposure exceeding 1200 hours. Absorption was studied at 260°C to 425°C and hydrogen pressures up to 2.0 MPa above equilibrium. Desorption was with a few exceptions done at 400°C at hydrogen pressures below 150 kPa. For practical application the hydrogen exchange may be limited to 75 - 90% of the complete metal to stoichiometric hydride reaction.

A change of the macroscopic structure of the powder into a highly porous, sintered agglomerate did neither reduce the hydrogen capacity nor the reaction rate. Although this change in structure caused no deterioration of the cycling performance a further development may not be acceptable. For observation over a much larger number of cyclings a fully automated, triple line cycling facility permitting simultaneous testing under different conditions have been constructed.

LECTURES

Conductivity, Structure and Specific Heat of $LiBiO_2$.

N.H. Andersen, F.W. Poulsen and G. Eichinger, presented at the 2nd European Conference on Solid State Chemistry, Eindhoven, Holland, 7-9 June 1982. (To be published in Solid State Chemistry).

Ac-conductivity, X-ray- and neutron powder diffraction- and DSC- experiments on solid and molten Li_2O-Bi_2O_3 mixtures are reported. The ionic conductivity of $LiBiO_2$ varies from approximately 10^{-7} at 200°C to 0.3 $(ohm.\ cm)^{-1}$ at 650°C. An abrupt increase in the conductivity occurs above 500°C. DSC- measurements on $LiBiO_2$ confirm the existence of anomalous thermal properties above 550°C. The neutron diffraction experiments on $LiBiO_2$ above 550°C, however, revealed no change in the crystal structure compared to the room temperature results. Structure refinements on the room temperature data gave results in qualitative agreement with the structure obtained from X-ray data reported in literature.

Experience with Ductile Crack Growth Measurements applying the DC-PD Technique to Compact Tension Fracture Specimens.

C.P. Debel and F. Adrian, presented at the OECD-CSNI Workshop on Test Methods for Ductile Fracture, Paris, 1-3 December 1982. (Transcript available).

The objective of this paper is to present the experience obtained at Risø in applying the direct current potential difference (DC-PD) technique to the indication of ductile crack initiation as well as to the quantitative measurement of the ductile tearing itself. The technique is used in connection with single specimen J_R-curve tests, employing compact tension (CT) specimens which may or may not contain side-grooves. The technique is based on the establishment of reference-curves, relating the change in electrical potential to the increase in ductile crack length in the CT-specimen.

Atlas of Defects revealed by Neutron Radiography in light Water Reactor Fuel.

J.C. Domanus, presented at the 50th Anniversary of the Discovery of the Neutron: The Neutron and its Applications, Cambridge, 13-17 September 1982. (Transcript available).

The assessment of neutron radiographs of nuclear fuel elements can be much easier, faster and simpler if reference can be made to typical defects, which can be revealed by neutron radiography. During the assessment of neutron radiographs some typical defects are found in the fuel and it was felt that a classification of such defects is necessary. Therefore such a classification was adopted by the Euratom Neutron Radiography Working Group and Risø National Laboratory has compiled an atlas of reference neutron radiographs on behalf of Euratom. It contains a collection of defects revealed by neutron radiography in light water reactor fuel, which are reproduced on X-ray film (original size) and as enlargements (two times) on photographic paper.

The contents of the atlas, showing a typical nuclear fuel pin and its elements, the classification of the revealed defects as well as all neutron radiographs of the atlas on X-ray film and photographic paper are reproduced on an illuminated table for poster presentation.

Standardization Activities of the Euratom Neutron Radiography Working Group.

J.C. Domanus, presented at the 50th Anniversary of the Discovery of the Neutron: The Neutron and its Applications, Cambridge, 13-17 September 1982. (Available as Risø-M-2356).

In 1979 a working group on neutron radiography was formed at Euratom. The purpose of this group is the standardization of neutron radiographic methods in the field of nuclear fuel. First priority was given to the development of a classification of defects revealed by neutron radiography in nuclear fuel. Following that classification a collection of reference neutron radiographs was published illustrating typical defects covered by the classification. Next, image quality indicators and standard objects for the determination of accuracy of dimensional measuremets from neutron radiographs were considered by the group. For that purpose beam purity and sensitivity indicators as well as a calibration fuel pin were designed and fabricated at Risø. All the Euratom neutron radiography centers will perform comparative neutron radiography with those items. The measuring results obtained, using various measuring apparatus, will form the basis to formulate conclusions about the best measuring methods and instruments to be used in that field.

Besides the atlas of neutron radiographic findings in light water reactor fuel, the Euratom Neutron Radiography Working Group has published a neutron radiography handbook in which the neutron radiography installations in the European Community are also described.

Nuklear og ikke-nuklear anvendelse af neutron radiografi. (Nuclear and Non-Nuclear Application of Neutron Radiography).

J.C. Domanus, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982. (Not available).

Principles of neutron radiography were given. Radiation sources used for radiography were reviewed. Production of neutrons was explained. Several examples of non-nuclear applications of neutron radiography were given. Risø activities in the field of neutron radiography of nuclear fuel were detailed by giving the description of the double-beam neutron facility, description of exposure procedures, defects revealed in nuclear fuel and international standardization activities.

Computerized Hydraulic Scanning System for Quantitative Non-Destructive Examination.

H.E. Gundtoft, presented at the 10th World Conference on Non-Destructive Testing, Moscow, 20-27 August, 1982. (Proceedings to be published, available as Risø-M-2331).

The Dependence of Flow Stress upon Grain Size for Non-Ferrous Metals and Alloys.

N. Hansen, presented at the Conference on Yield, Flow and Fracture in Polycrystals, Glasgow, 15-16 September 1982. (Proceedings to be published).

The flow stress/grain size relationship of a number of non-ferrous metals and alloys may be expressed by a modified Petch-Hall equation:

$$\sigma(\varepsilon) = \sigma_o(\varepsilon) + k(\varepsilon)\, d^{-1/2}$$

where $\sigma(\varepsilon)$ is the flow stress at constant strain, d is the grain size, and $\sigma_o(\varepsilon)$ and $k(\varepsilon)$ are constants.

The dependence of flow stress on grain size also may be derived on the basis of relationships between the dislocation density, the plastic strain and the grain size. A variety of equations correlating the flow stress and the grain size have been obtained by assuming different dislocation distributions in the deformed microstructure, for instance a uniform dislocation distribution or a composite deformation substructure.

Experimental data for the grain size dependence of the flow stress for a number of non-ferrous metals is reviewed in this paper, with special emphasis on the behaviour of aluminium and copper. Furthermore, the effect of dispersed particles on the flow stress/grain size dependence is discussed.

Deformation structures have been studied by different techniques, e.g. bulk substructures by transmission electron microscopy and surface displacements by replica examinations. These observations are discussed and where possible correlated with the mechanical data.

EF's Energiforskning. (Energy Research in the EEC).

N. Hansen, presented to Selskabet for Europaforskning, Sandbjerg Slot, 26-27 February 1982. (Not available).

A short resume and a discussion of the energy research within EF.

Apparatus for Dynamical Texture Measurements by Neutron Diffraction using a Position Sensitive Detector.

D.J. Jensen, presented to Forårsskole om Neutronspredning, Wehlen, DDR, 1-5 March 1982; Dansk Fysisk Selskab, Nyborg, May 1982; Dansk Krystallografimøde, Risø, 17-18 May 1982. (To appear in Textures and Microstructures).

A new apparatus for dynamical texture measurements using neutron diffraction has been developed. A variable wavelength neutron spectrometer has been modified to incorporate a linear position-sensitive detector. The sample is orientated by a fully automatic Euler goniometer, and it can be heated by a stream of hot air at rates up to 200°C/min. A quarter of a complete pole figure can be recorded in 14 minutes with an accuracy, determined by counting statistics, of 2-3%.

Magnesiumpulver som energilager. (Magnesium Powder for Energy Storage).

J. Kjøller, presented to Dansk Forening for Materialografi, Kolding, 18-19 November 1982. (Not available).

A description of the metal-hydrogen energy concept is given with emphasis on the experimental work carried out at Risø, Metallurgy Dept. Advanced equipment and technologies developed specifically for the hydride research are discussed in some detail.

Nye perspektiver i brændselselementforskning. (New Perspectives in Fuel Element Research).

P. Knudsen, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982. (Transcript available, 9 pp.).

The purpose of RISØ's fuels development program is to ensure a good knowledge of fuel element design, fabrication and performance. This is obtained in a combination of Danish R & D and broad international collaboration.

Testing of Danish fuel with satisfactory results has comprised.

- 10 fuel elements in the Halden reactor (Norway)
- 4 fuel elements in the Kahl reactor (W. Germany)
- more than 150 test fuel pins in the DR 3 reactor (RISØ). This work includes extensive hot cell examinations and analyses with Danish fuel performance codes. Additional experience is obtained from examination of foreign fuels from test and power reactors.

The experience obtained provides the basis for:

- competent consulting to authorities, utilities and industry,
- internationally sponsored R & D programs on the performance of high-burnup fuel,
- development of advanced equipment and methods for hot cell examinations.

The perspectives of the RISØ development are illustrated with a series of examples from completed and ongoing fuels development programs.

Kontrol og prøvning af vinger til Nibemøllerne. (Control and Testing of the Wingblade-Sections for the Nibe Wind Turbines).

H. Lilholt, presented to Plastsammenslutningen, Industriens Hus, Copenhagen, 30 September 1982. (Not available).

The control and test methods applied during design and fabrication of the 12 m wing blade-rections for the Nibe wind turbines are presented.

Egenskaber for armeret plast i sammenligning med andre materialer. (The Properties of Fibre Reinforced Plastics as compared with those of other Materials).

H. Lilholt, presented to Plastsammenslutningen, Industriens Hus, Copenhagen, 30 September 1982. (Not available).

The mechanical properties of fibre reinforced composite materials are presented, as well as properties of the reinforcing fibres.

Glasfiberarmeret polyester. (Glass Fibre Reinforced Polyester).
H. Lilholt, presented to Ingeniør-Sammenslutningen, Domus Technica, Copenhagen, 21 January 1982. (Not available).

A presentation of glass fibre reinforced polyester and its mechanical properties, with special reference to the building materials.

Fiberforstærkede kompositmaterialer. (Fibre-reinforced Composite Materials).
H. Lilholt, presented to the Danfoss Company, Nordborg, Als, Denmark, 28 May 1982. (Not available).

A presentation of a number of fibres, their properties and use in composite materials; and a presentation of the mechanical properties of composite materials.

Tilsætningsmaterialernes betydning for kompositegenskaberne. (The Effect of Fillers on the Composite Properties).
H. Lilholt, presented to Polymerteknisk Selskab, The Technical University of Denmark, Lyngby, 12 January 1982. (Not available).

A brief presentation of the mechanical properties of fibre-reinforced composite materials.

Spredte indtryk om kompositmaterialer i Japan. (Miscellaneous Impressions of Composite Materials in Japan).
H. Lilholt and N. Christiansen, presented at Teknologirådets temadage om kompositmaterialer, Tåstrup and Århus, 30 November and 1 December 1982. (Not available).

A brief presentation of the status and development of composite materials in Japan is given.

Fiberkompositter til hårdt belastede konstruktioner. (Fiber-composites for Heavily Loaded Constructions).

Aa. Lystrup, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982; Maskinafdelingens 25 års jubilæum, Danmarks Ingeniørakademi, Lyngby, 13 August 1982; Dansk Forening for Materialografi, Kolding, 18 November 1982. (Not available).

An overview was given of industrial applications of advanced fibre composites. Methods of analysis, production and quality control were described. Research and development in the field of composite materials in the Metallurgy Department, Risø, were surveyed.

Determination of Retained Gas in Irradiated Fuel Samples.

M. Mogensen, presented at the EEC Hot Laboratory Committee Meeting, Mol, Belgium, 10-11 June 1982. (Transcript available).

Full cross section samples from water reactor fuel pins are oxidized in molten $NaNO_3$ containing about 10% NaOH and 5% Na_2O_2. During this oxidation the fission gases Kr and Xe are released. The gas volume is measured, and the gas is analysed by mass spectrometry.

The generated amount of gas in the samples analysed is calculated from measured burn-up, from measured Xe and Kr isotope ratios and from fission yields of stable Xe and Kr isotopers with low neutron capture cross sections. From the fission gas generated and measured amount of gas retained, the gas retention and release percentage can be found.

Examples of results are reported. Retained gas plus released gas (measured by puncturing) and the calculated gas generation agreed within 6 percent.

Determination of Fission Gas Yields from Isotope Ratios.

M. Mogensen, presented at the 9th International Mass Spectrometry Conference, Vienna, 30 August - 3 September 1982. (Proceedings to be published, will also appear in the International Journal of Mass Spectrometry and Ion Physics).

This paper describes a method of calculating the actual fission yield of Kr and Xe in nuclear fuel including the effect of neutron capture reactions and decay. The bases for this calculation are the cumulative yields of Kr and Xe isotopes (or pairs of isotopes) which are unaffected by neutron capture reactions, and measured Kr and Xe isotope ratios. Also the burnup contribution from the different fissile heavy isotopes must be known in order to get accurate fission gas yields.

Mass Spectrometric Measurements of Fission Gas From Nuclear Fuel.

E. Larsen, A. Egsgård and M. Mogensen, presented at the 9th International Mass Spectrometry Conference, Vienna, 30 August - 3 September 1982. (Proceedings to be published, will also appear in the International Journal of Mass Spectrometry and Ion Physics).

Isotopic and quantitative measurements of the fission gases Xe and Kr in fuel pins are presented. The gas extracted by puncturing a fuel pin and the retained gas released by oxidizing fuel pellet size samples are compared with the calculated amount of fission gas generated.

On the Surface Reaction of Hydrogen with FeTi.

A. Schrøder Pedersen, presented at the Nordic Conference on Surface Science, Tampere Technical University, Tampere, Finland, 18-29 August 1982. (To appear in Physica Scripta).

The surface reaction of hydrogen (and of deuterium) with activated FeTi was studied by UHV volumetric vapour pressure measurements in the 3×10^{-8} Pa to 1.3×10^{-5} Pa range at 78 K and 88 K.

At the low temperatures a dissociative non-activated Temkin chemisorption process was found. An isosteric heat of adsorption, q, was described by the expression $q = 24(1-\theta)$ KJ/(mole H_2) for a broad range of coverages. It was demonstrated that the dissociation occurred on a non-oxidized Ti-surface and not - as often suggested - on a segregated subsurface Fe-layer.

Composite Principles in Metal Fatigue.

O.B. Pedersen, presented to the Fatigue Thrust Group, Northwestern University, Evanston, Illinois, 8 December 1982. (Not available).

The recent development of rigorous composite principles which may be combined with dislocation theories of stress relaxation and obstacle controlled flow was discussed. The application of these principles in experimental studies has clarified some of the similarities and differences between the cyclic and the monotonic deformation of single crystals and polycrystals of pure copper. It is hoped that current work on the effect of non-shearable particles, fibres and grain boundaries on the fatigue strength of copper will contribute to a better understanding of the fatigue strength of more complex alloys.

Lithium Ion Conduction in Solid Two Phase Mixtures Containing LiI.

F.W. Poulsen and N.H. Andersen, presented at the Topical Meeting on Physical Properties of Disordered Systems, Danish Physical Society, Lyngby, 4 October 1982. (To appear in Solid State Ionics).

Cubic LiI is a relatively poor Li-ion conductor, i.e. the specific conductivity at 25°C is 10^{-7} $(\text{ohm cm})^{-1}$. The conductivity of polycrystalline LiI can be increased by a factor of 100 to 1000 by making an intimate mixture of LiI with a second solid material with a large specific area. Conductivity data for LiI-Al_2O_3 mixtures are presented as function of the following parameters: composition, temperature, and fabrication method. The possible origins of the conductivity enhancement are shortly discussed.

Kemisk fornikling. (Electroless Nickel Plating).

K. Rørbo, presented of Danish Forening for Materialografis Temadag: Overflader og Lag, Tåstrup, 30 September 1982. (Not available).

The principles of electroless nickel plating (including mechamisms, both compositions catalysts etc.) were reviewed. The characteristic properties of the deposits (structure and composition, heat treatment, melting point, uniform thickness, corrosion resistance) were discussed and examples of applications of electroless nickel plating are given.

Nucleation, Growth and Distribution of Cavities under Fission and Fusion Irradiation Conditions.

B.N. Singh, presented at the Institut für Festkörperforschung, Kernforschungsanlage Jülich, 14 December 1982. (Not available).

Theoretical aspects of void and bubble nucleation will be reviewed. A nucleation theory based on "agglomeration" of vacancy-gas atom complexes will be discussed; effects of helium as well as residual gases will be considered. Experimental results showing the effects of alloying on structural variables (e.g. dislocations, dislocation walls and grain boundaries) on cavity nucleation and growth under different irradiation conditions will be described and discussed.

Udvikling af avancerede batterier for lagring af elektrisk energi. (Development of Advanced Batteries for Storing Electrical Energy).

O. Toft Sørensen, presented to Norsk Kemisk Selskab, Norges Tekniske Universitet, Trondheim, Norway, 9 March 1982. (Not available).

In this lecture was presented a review on the state of art in the development of advanced batteries for storage of electrical energy as well as potential applications of three batteries in the future. The topics covered were: (1) General description of battery systems; (2) Properties required (energy and effect density) (3) Potential materials, (4) Primary Lithium batteries; (5) Reversible batteries; (6) Projects at Risø and (7) Potential applications.

Defekte oxider. (Defective Oxides).

O. Toft Sørensen, presented to students at Norges Tekniske Universitet, Trondheim, Norway, 10 March 1982. (Not available).

A general introduction to defective oxides was presented in two lectures. The topics covered were: (1) Defect types; (2) defect equilibria (3) Brouwer plots; (3) Thermodynamic properties; (4) Phase relationships (5) Structure of defect oxides; (6) Transport properties and (7) Electrical properties.

Elektrodematerialer til avancerede batterier. (Electrode Materials for Advanced Batteries).

O. Toft Sørensen, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982. (Not available).

In this lecture was presented the background and the results obtained in two anode projects: (1) Anode materials for primary batteries ($Li/SoCl_2$) and (2) Anode materials for reversible batteries. In the first project the cause for delayed action in the $Li/SOCl_2$ battery is examined whereas all solid state lithium alloys are developed in the second project for batteries.

Keramiske iltionledere for iltmålesonder. (Ceramic Oxygen Ion Conductors for Oxygen Sensors).

O. Toft Sørensen, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982. (Not available).

After a short introduction describing the general properties of oxygen conductors the materials research project on CeO_2-Gd_2O_3 conductors at Risø was presented. Finally the potential application of these in oxygen sensors and in fuel cells was briefly discussed.

Quasi-Isothermal Methods in Thermal Analysis.

O. Toft Sørensen, plenary lecture at the 7th Nordic Symposium on Thermal Analysis, Helsinki, 14-16 June 1982. (Not available).

In this plenary lecture was presented a review on the different quasi-isothermal methods used in thermal analysis. The advantages of the method developed at Risø were then discussed and several examples of the use of this method in thermogravimetric and dilatometric measurements were presented. Finally the methods developed for evaluating kinetic data from experimental results obtained by this technique was described and the reliability of these methods was demonstrated by data obtained in quasi-isothermal dilatometric studies on UO_2 powder compacts, which gave activation energies and diffusion coefficients for the first sintering stage which correspond well with literature data.

Quasi-Isothermal Analysis: A New Technique in Thermogravimetry and Dilatometric Sintering Studies.

O. Toft Sørensen, presented to Students at Massachussetts Institute of Technology, Cambridge, USA, 12 August 1982. (Not available).

After a short introduction in which the principle of the quasi-isothermal technique was described, some examples of the application of this technique in thermogravimetric and dilatometric measurements were described in order to show the advantages of this method. The methods developed for evaluating kinetic data (reaction mechanism, activation energy, diffusion coefficient) from the experimental data obtained by this technique was then discussed and it was shown that kinetic data for the first and second sintering stage of UO_2 powder compacts determined by quasi-isothermal dilatometry correwell with literature data, which indicates that these methods are accurate and reliable.

Quasi-Isothermal Dilatometric Studies of the Influence of Oxygen Pressure on the Initial Sintering Stage of UO_2 Powder Compacts.

M. El Sayed Ali, O. Toft Sørensen and L. Hälldahl, presented at the 7th Nordic Symposium on Thermal Analysis, Helsinki, Finland, 14-16 June 1982. (To appear in J. Thermal Analysis).

Quasi-isothermal dilatometry (QID) is a useful technique for sintering studies of powder compacts. In the present work the principle of this technique and the method of calculating activation energies from QID curves is first described; then, using this method, the sintering mechanism and the influence of oxygen pressure on the initial sintering stage of UO_2 compacts are evaluated. The controlling mechanism was found to be grain boundary diffusion of uranium vacancies with an activation energy of 56 kcal/mole in according with literature data.

The Use of Quasi-Isothermal Dilatometry in Evaluation of the Initial Stage of Sintering UO_2 Powder Compacts.

M. El Sayed Ali and O. Toft Sørensen, presented at the 7th International Conference on Thermal Analysis, Kingston, Ontario, Canada, 22-28 August, 1982. (Proceedings to be published).

Quasi-isothermal dilatometry (QID) is a new sintering technique, which has the advantage that kinetic data, diffusion coefficients and optimum sintering conditions can be determined in a single experiment. Int the present paper is described a new method for evaluating kinetic data from the experimental QID curve. This method is then used to evaluate the initial sintering stage of UO_2 powder compacts and it is shown that both the activatenergy and diffusion coefficients obtained compare well with literature data.

Magnesiumhydrid som energilager. (Magnesiumhydride as an Energy Store).

B. Vigeholm, presented at Metallurgiafdelingens Industrimøde, Risø, 20 April 1982. (Not available).

Among the known metal hydrides, MgH_2 is the one which is most likely to meet the economical technological and environmental requirements to a useful energy store. The most important parameters in the magnesium-hydrogen reaction has been investigated along with materials technological properties important to its applicability. Special emphasis is given to materials properties, reaction-conditions and contamination effects.

Formation and Decomposition of Magnesium Hydride.

B. Vigeholm, presented at the International Symposium on the Properties and Applications of Metal Hydrides II, Toba, Japan, 30 May - 4 June 1982. (Manuscript published in J. Less-Common Metals, 89 (1) (1983) 135-144).

The absorption of hydrogen in magnesium, 99.8-99.94% was studied at 260°C and 425°C and pressures between equilibrium and 2 MPa above. At constant temperature the absorption rate depends on the pressure whereas the total sorption is attained in largely the same time. The final composition is very close to stoichiometric MgH_2 when deduction of present oxide is made. Exceptions are the lowest temperatures and highest pressures. In both of these cases the reaction is becoming extremely slow or ceasing completely above 80-90%. Accurate determination of the relative molar enthalpy gives a slightly higher value, -70 kJ/mol H_2, than previously recorded. No hysteresis in the ordinary sense was observed, but althouth no change in plateau pressure occured, desorption from 5-15% remaining hydrogen required almost zero pressure. The actual value seems dependent on the material.

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